



A novel magnetic field probing technique for determining state of health of sealed lead-acid batteries

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H I G H L I G H T S

- Paper demonstrates the magnetic field probing as a battery health diagnostic tool.
- Magnetic field probing is a non-invasive way to measure LA battery health.
- It is possible to analyze the electrode surface structure using MFP.
- Acid stratification and non-homogeneous participation of electrodes is inferred.

A R T I C L E I N F O

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State of Health (SOH) is a critical index for a Sealed Lead-Acid (SLA) battery diagnostic which provides the information about battery replacement and aging effects. SOH is a complex function of chemical parameters of a battery such as stratification in electrolyte, electrode structure (sulfation and hard sulfation) in addition to electrical parameters of a battery. This paper describes a method of online determination of stratification, electrode structure, electrode polarization and current profile within the battery under the influence of a magnetic field. An AC magnetic field is used as a noninvasive tool during battery cycles. An induced emf in a secondary coil (SCV) is used as a measure of change in the magnetic field.

The H^+ proton density varies with change in sulfuric acid (electrolyte) concentration during battery cycles. The magnetic flux lines are affected by the density of H^+ protons whose magnetic dipole moments try to align along the magnetic flux lines. The stratification is seen by a 12% decrease in magnetic flux linking from the top to the bottom of the electrolyte in a battery. Additional experimental results demonstrate the variation in magnetic flux linking which correlates with current profile across the electrode and electrode structure.

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1. Introduction

Battery health and charge monitoring are important issues for the operation of electric vehicles (EVs) or hybrid electrical vehicles (HEVs) systems. Battery State of Charge (SOC) is interpreted as a present charged state which depends mostly on electrical parameters of a battery. Poor SOC of a battery indicates the need for battery charging. By contrast the state of health (SOH) of a battery is indicative of its need for conditioning to restore its power delivery capability or replacement. SOH is a complex function of battery

aging effects, cycles, stratification, and hard sulfation (premature capacity loss) of electrodes in a lead-acid (LA) battery.

$SOH = f(\text{battery aging, stratification, electrode's sulfation, irregular cycles})$

These aging effects of an operating battery are difficult to interpret due to intermingled electrical and chemical parameters. Additionally, real time or on-load SOH also depends on chemical reaction rates, electrode structure changes, electrolyte concentration gradient, polarization of electrodes, and motion of ions in the electrolyte (current profile in the battery).

Different researchers have tried offline analysis of sulfation of the electrodes, electrolyte stratification, and electrode health deterioration due to aging. Guo *et al.* [1] have studied the effect of

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electrolyte stratification on the performance of the flooded LA battery in offline condition. They used a sulfuric acid (H_2SO_4) specific gravity sensor and in-situ electro-chemical scan technique to measure the current distribution on the plates. They analyzed the effect of charging and discharging on the surface of the electrodes offline. Mattera *et al.* [2] studied the premature capacity loss in LA batteries due to stratification in photovoltaic systems. The authors worked on a prototype cell with a reference cell (two negative and a single positive electrode). Later, radioelement detection was used to characterize the premature capacity loss. However, currently there is no direct method available to measure stratification, sulfation and current distribution within the battery during on-load conditions.

Magnetic field probing for state of charge (SOC) estimation in batteries has been studied recently. Hill *et al.* [3] determined the SOC of a LA battery using wire wound coils attached to the plastic case of the battery, adjacent to the negative electrode plate. An AC signal of 10 kHz was used to excite the coil. The change in the SOC was inferred by the change in the self and mutual inductance of the coil. Tinnemeyer [4,5] used magnetic susceptibility measurements on a battery sample. The author used a sensor to measure the variation in magnetic susceptibility of lead/lead sulfate electrodes to estimate the SOC of the battery. He also used a magnetic tunneling junction sensor on a Li-ion battery to predict its state of charge.

P.R. Stevenson [6], reported using a coil attached to the negative electrode of a SLA battery introduced an eddy current in the negative electrode. He then inferred SOC by observing the change in energizing signal frequency and amplitude due to eddy current opposition. D. Limuti *et al.* [7] used an energized coil close to the electrode and measured the complex impedance of the coil. They also used a capacitive sensor along with a coil for sensing the electrolyte level. This is possible only with a flooded lead-acid battery. In the patent Limuti claims to observe battery voltage, SOC, electrolyte level, internal resistance and temperature using a combination of coil and capacitive sensors. J.F. Beutler *et al.* [8] used a coil positioned relative to the predefined volume (battery) to minimize the reluctance path between the coil and the electro-chemical process. They observed the change in complex impedance of the coil and obtained SOC as a function of complex impedance of the coil.

Previous researchers have used electromagnetic field probing methods as described above exclusively for indicating SOC of a battery none of them addresses determination of SOH of the battery.

The present work describes the use of a noninvasive magnetic field probing method to induce stratification, electrode structure and current profile for indicating the SOH of a battery. The battery behavior was observed during the charging and discharging cycles of a SLA battery. The magnetic field is generated by placing two identical coils across the battery. The battery is placed in the magnetic field in such a way that the outside magnetic flux lines and internal electric field lines between the electrodes are perpendicular to each other. The flux lines are generated by a primary coil and linked to a secondary coil after passing through the battery.

The change in the magnetic field response (MFR) or in magnetic flux lines across the battery occurs mainly due to the following reasons:

- internal electric field variation during the charging and discharging cycles of the battery
- change in the susceptibility of the electrodes
- electric field generated due to drift voltage at the electrodes (battery terminal)

- change in H^+ proton concentration which has magnetic dipole moments; and
- whether, the battery electrode plates are perpendicular or parallel to the magnetic flux lines.

The changes in MFR or magnetic flux linkage between the primary and secondary coils are measured by induced electromotive force (emf) in the secondary coil. Previous researchers either used complex impedance between electrode and external coil or susceptibility change at electrodes using a tunnel junction sensor. The change in induced emf (mV) or secondary coil voltage (SCV) is an indication of the battery behavior and its internal health. In this paper, MFR measurements are used to predict following:

- Electrolyte concentration gradient horizontally and vertically in the physical structure of the battery;
- The reaction rate on the electrodes' surface; and
- The electrodes' polarization (Due to the polarization of the electrodes a drift voltage appears across the electrodes and it develops an electric field. The drift electric field is perpendicular to magnetic field and affects the magnetic flux linking.).

This study was carried out using a SLA battery and a preliminary test setup. Our work focuses on H^+ proton concentration that correlates to MRF measurements and interprets it for acid stratification, electrode's structure and current profile in a battery.

2. Basic theory

The voltage SCV ($V_2(t)$) is directly related to the concentration of H^+ protons in the battery.

Consider a sinusoidal applied current in the primary coil $I_1(t)$ as given in equation (1),

$$I_1(t) = I_{01} \sin \omega t \quad (1)$$

then

$$V_2(t) = M_{12} \frac{\partial I_1}{\partial t} = \omega M_{12} I_{01} \cos \omega t \quad (2)$$

where, M_{12} is the mutual inductance of the two coils and $V_2(t)$ is induced emf in secondary coil. The mutual inductance of the two coils is given in equation (3)

$$M_{12} = \mu a G(k), \quad (3)$$

where, $k^2 = (4a^2/(4a^2 + d^2))$ and a and d are the radius and the distance of the coils respectively. The function $G(k)$ is a smooth function of variable k . For the current study, we have $a < d$, therefore, $k \equiv (2a/d)$.

Hence, the function G is approximately

$$G(k) \equiv \frac{\pi}{2} \left(1 - \frac{5}{8}k - \frac{1}{64}k^2 + \dots \right) \approx 1.57 - 0.982 \left(\frac{a}{d} \right) - 0.024 \left(\frac{a}{d} \right)^2 + \dots \quad (4)$$

μ is the permeability of the material in the volume between the coils, which includes all the parts of the battery electrolyte and the electrodes.

$$\mu = \mu_0(1 + \chi_m) \quad (5)$$

where χ_m and μ_0 are the susceptibility of the electrolyte and the permeability of air, respectively. χ_m is proportional to the proton concentration $n_p(t)$ and the proton dipole magnetic moment μ_p . Therefore, by equations (2)–(5) the instantaneous amplitude of the



Fig. 1. Test experimental setup.

induced voltage in the secondary coil $V_2(t)$ (SCV) is directly related to the instantaneous value of the proton concentration,

$$V_2(t) = An_p(t) \quad (6)$$

A is a proportionality constant, if all the other geometrical factors are kept constant.

The measured SCV is the voltage change $\Delta V_2(t)$ during the charging and discharging process and is given by equation (7)

$$\frac{\Delta V_2(t)}{V_2(0)} = \frac{n_p(t)}{n_p(0)} \quad (7)$$

$V_2(0)$ and $n_2(0)$ are initial SCV and proton concentration respectively. Equation (7) clearly indicates the relation between SCV and H^+ proton concentration. SCV here is a measure of MFR.

3. Experimental setups

3.1. Simulated battery test setup

This work first was verified by the measurements and observations with a preliminary test setup shown in Fig. 1. The experimental setup was designed using a glass jar half filled with water. The concentrated sulfuric acid was poured on the top of the water and the jar was left to rest for 10–12 h. The heavy sulfuric acid settled down to the bottom of the jar and created a clear stratification condition. This jar was then moved between the coils to observe the effect of stratification under a magnetic field. The primary coil was excited with an AC input signal of frequency 70 kHz and amplitude 625 mV. Coils were placed 12 cm apart and SCV was observed in the secondary coil. The test results, given in Table 1, demonstrate that concentrated acid reduces the flux linkage in the secondary coil and so does SCV. The water content increases the flux linkage.

In another set of experiments with the test setup, two lead plates (oxidized due to atmosphere) were inserted in the stratified acid jar. The plates were positioned facing the coils and parallel to the coils. The SCV was then observed. It was noticed that when the metal (Pb) plate is facing the magnetic lines it screens most of the flux lines due to eddy losses through the metal plate. On the other

hand when the plate is placed parallel to the magnetic flux lines it increases the strength of the magnetic flux linkage and increases SCV too.

3.2. SLA battery setup

We have observed the battery behavior (stratification, electrode structure and current profile) using magnetic field probing, by placing a 12 V Genesis SLA battery in an AC magnetic field. The battery was placed between two identical, coaxial, coils such that the axis of the coils was parallel to the battery plates. Therefore, the external magnetic field was almost perpendicular to the internal electric field generated by the battery electrodes. The basic experimental setup is shown in Fig. 2.

The primary and secondary coils generating and detecting the AC magnetic field were each of 4.0 cm in diameter and 250 turns and were placed 16.3 cm apart across the battery width. The coil diameter is approximately 13% of the total length of the battery (29.5 cm). The length of the battery housed 6 pairs of electrodes having a 4.9 cm space for each pair. The primary coil was excited by an input signal of frequency 70 kHz and amplitude of 9 V. A general radio oscillator (1310 B) was used to generate the input AC signal for the primary coil. An HP 3561A Dynamic signal analyzer was used to measure the root mean square value (rms) of the induced emf at the secondary coil (SCV). Throughout this paper, SCV is used as an index for the performance of the battery under the magnetic field or MFR. The magnetic field was measured with a Hall effect probe (5100 F.W. Bell). The magnetic field was measured at distance of 16.3 cm which corresponds to the width of the battery and average radial component of the magnetic field was 19G. When the battery was placed between the coils (16.3 cm apart) the magnetic field at the secondary coil was 19.3G.

The battery behavior was inferred from the secondary coil induced emf measurement during the charging or discharging process. The battery monitoring system (BMS) charger was charging and discharging the battery with a 7 A constant current over a period of the order of 10 h.

We observed the electrolyte concentration gradient (stratification) under the charging and discharging process at various vertical and horizontal positions of the electrolyte level in the battery. The horizontal and vertical coil positions on the battery's external structure are shown in Fig. 3.

4. Observations and analysis

The observations are divided into three categories. (1) Battery performance under magnetic field during battery cycles, (2) SCV



Fig. 2. Basic experimental setup for magnetic field probing.

Table 1
Test setup results.

Medium for magnetic flux to travel	Air	Water	10% H ₂ SO ₄	25% H ₂ SO ₄	50% H ₂ SO ₄
Secondary coil voltage (SCV)	468.1 mV	440.5 mV	387.8 mV	339.6 mV	150 mV

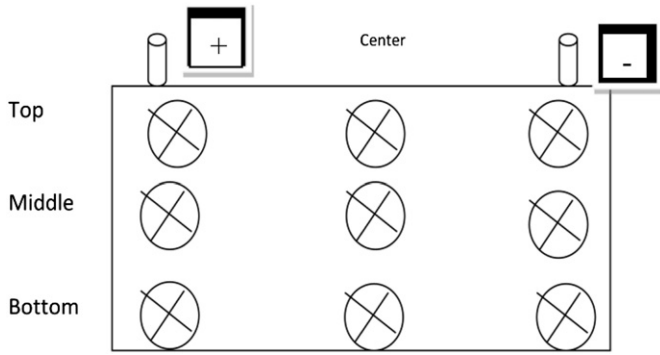


Fig. 3. (a) 3×3 Row and column coil positions on battery physical structure.

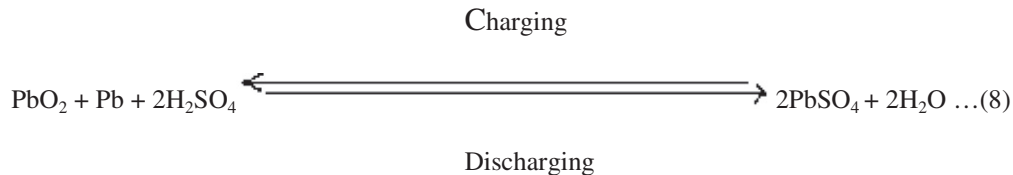
analysis for stratification of the stationary battery and (3) SCV at 3×3 coil positions during battery cycles for current profile and electrode surface structure.

4.1. Battery performance under magnetic field for battery cycles

It is essential to observe a battery under a magnetic field first, before running any other complex experiments. These observations are taken with a battery placed in an AC magnetic field generated by a coil and the responses are collected from an identical symmetric coil as SCV.

increasing the magnetic coupling between the coils. The test setup in Fig. 1 demonstrated that when the metal (Pb) plate is facing the magnetic lines it screens most of the flux lines due to eddy losses through the metal plate. On the other hand when the plate is placed parallel to the magnetic flux lines it increases the strength of the magnetic field and the SCV.

A discharged battery has a relatively low specific gravity compared to a fully charged battery because of a higher percentage of water in the electrolyte. This increases the H^+ proton concentration. Therefore, the discharged state of the battery shows better magnetic flux linkage between the coils (higher SCV) than the charged state of the battery. The H^+ proton concentration in the electrolyte and the magnetic flux linkage both vary with the specific gravity during battery cycling. The magnetic flux linkage decreases during charging and increases during discharging following the H^+ proton concentration variation in the electrolyte. Fig. 7 and equation (8) display the process. Alternatively, the charging cycle produces strong sulfuric acid which reduces the magnetic flux linking and the discharging cycle enhances the magnetic flux linking by diluting the acid. The fact is verified in Ref. [9] that described the diamagnetic susceptibility of water and sulfuric acid. Diamagnetism is the property of an object or material which causes it to create a magnetic field in opposition to an externally applied magnetic field. Fig. 8 shows the diamagnetic mass susceptibility of water ($-0.72 \times 10^{-6} \text{ cm}^3 \text{ g}^{-1}$) and sulfuric acid ($-0.40 \times 10^{-6} \text{ cm}^3 \text{ g}^{-1}$). The sulfuric acid has stronger diamagnetic susceptibility relative to water and hence it repels the



The magnetic flux linkage between two identical coils increases when the battery slides between the coils as shown in Fig. 4(a) and (b). The increase in the magnetic flux linkage is seen by SCV increases of 120–130%. The fully discharged battery showed at least 10–12% higher linkage of magnetic flux in comparison to the fully charged battery. The connection of the BMS charger to the battery also affects the magnetic flux linkage in the secondary coil. The BMS connection reduced the SCV by 25–30%.

The SCV is sensitive to the battery charging and discharging cycles. The magnetic flux linkage reduces the SCV from 234 mV to 228 mV (2.5%) upon charging the Armasafe 12 V, 120 A h capacity SLA battery for military vehicles as shown in Fig. 5. It increased around 10% in a Genesis 12 V XE70 battery during discharging as shown in Fig. 6. SCV measurement showed better sensitivity with the Genesis battery which was a relatively fresh battery compared to the Armasafe battery. Therefore we decided to use the Genesis battery for the rest of the experimental work.

The above observations can be explained by the fact that the battery establishes better magnetic linkage compared to air, because of the presence of H^+ protons in the electrolyte. The H^+ proton has a magnetic dipole moment $\mu_p = 2.8$ nuclear magnetons. When the battery is exposed to a magnetic field, H^+ protons align with the magnetic lines and hence enhance the magnetic flux linkage between the coils. The experimental setup is such that the battery electrodes are parallel to the magnetic flux lines and are

magnetic field more. This repulsion of concentrated sulfuric acid reduces magnetic flux linking.

The logic also aligns with Ref. [4] where the author described the electrode's diamagnetic susceptibility while charging and discharging of the lead-acid battery. During charging, lead sulfate of the electrodes converts into lead oxide at the positive plate and lead at the negative plate. The diamagnetic susceptibility of the electrodes increases from $-69.7x_m/10^{-6} \text{ cm}^3 \text{ mol}^{-1}$ to $-42x_m/10^{-6} \text{ cm}^3 \text{ mol}^{-1}$ for lead oxide and to $-23x_m/10^{-6} \text{ cm}^3 \text{ mol}^{-1}$ for lead. The strong diamagnetic susceptibility reduces the magnetic flux linkage and hence charging makes magnetic flux linkage weak. The opposite is the case during discharging, where, a decrease in the electrode diamagnetic susceptibility improves the magnetic flux linkage. The author showed only the electrodes status change by diamagnetic susceptibility during charging and discharging. However, in this paper, we have used an argument of H^+ proton concentration variation in the electrolyte to indicate battery state of charge and state of health (acid stratification and sulfation).

The internal electric field of the battery also affects the magnetic flux linkage. As the internal electric field increases with charging of the battery, it screens the perpendicular magnetic field and thus reduces the magnetic flux linkage (SCV) at the secondary coil. During discharging, the internal electric field through the electrodes is reduced, providing a free path for magnetic flux lines to pass through the electrolyte. This effect enhances the magnetic flux at the secondary coil.

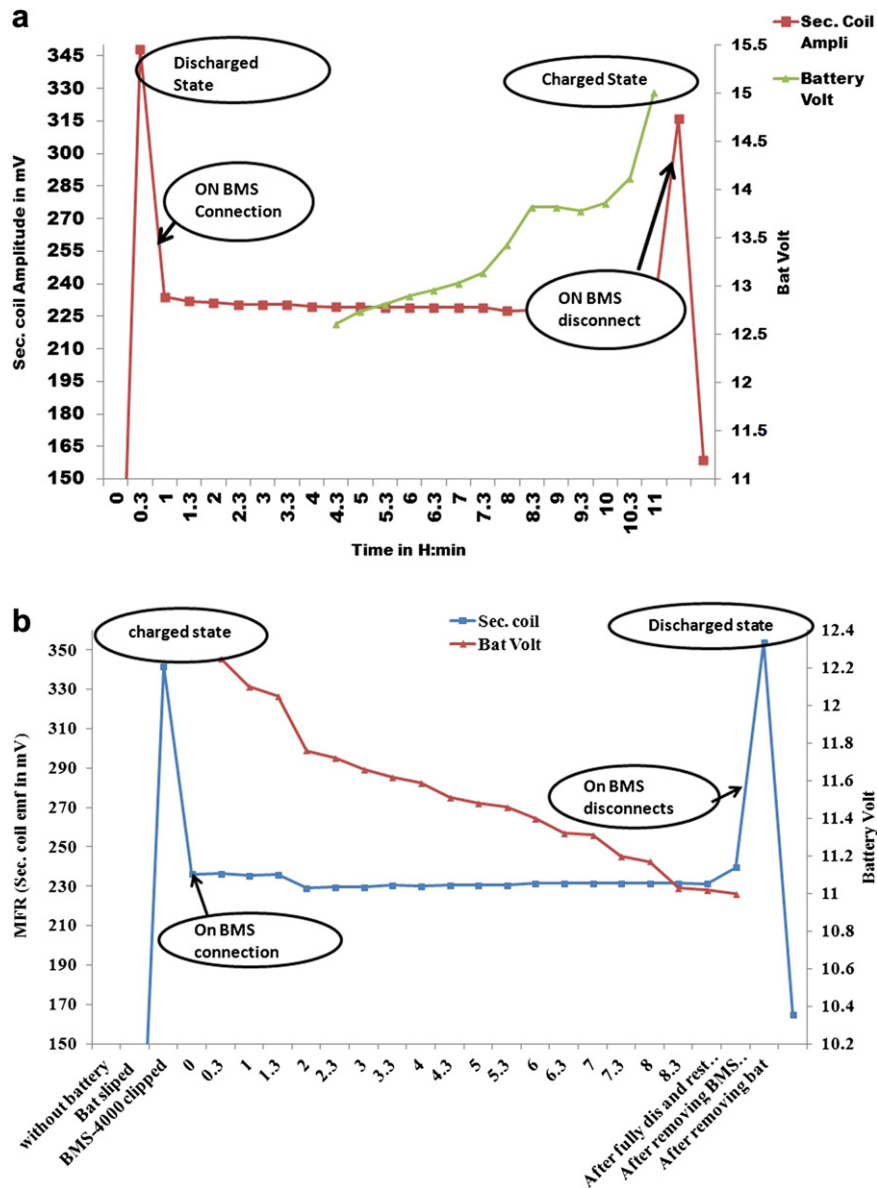


Fig. 4. (a): Battery charging under the influence of magnetic field. (b): Battery discharging under the influence of magnetic field.

It has been observed that the BMS charger connection to the battery terminal alters the magnetic flux linkage. The BMS charger applies a DC voltage of around 5 V at the battery terminal and polarizes the electrodes. In response, the electrodes generate an electric field perpendicular to the existing magnetic flux lines as shown in Fig. 9. This electric field interacts with the perpendicular magnetic field and screens the magnetic flux lines at the secondary coil. This observation can be a significant probe for measuring online electrodes polarization in a battery.

4.2. SCV analysis for stratification of a stationary¹ battery

This set of measurements has been taken by a pair of coaxial coils situated at various vertical positions for a fixed horizontal position at the battery's external frame. The three horizontal positions chosen were the center of the battery and the positive and

negative electrodes. The vertical positions at the center are marked in Fig. 10. The vertical positions at the electrodes are the same as the positions at the center. The battery is in the equilibrium/stationary¹ condition at the fixed discharged state.

Fig. 11 shows the results of magnetic flux linking (SCV) observed at different coil positions. SCV values at the electrodes are smaller in comparison to the corresponding values at the center of the battery. The negative electrode (Pb) screens more magnetic flux compared to the positive electrode (PbO₂). At the vertical top position 'A', SCV has the lowest value. The position 'B' shows the highest SCV. At position 'C' SCV is lower than the position 'B', but still higher than at the 'G' (Ground) position.

The SCV values are higher by an average of 4.8% at the center positions of the battery than those at the electrodes because, we assume, the center positions provide free passage for the magnetic flux lines without electrodes in their path. The battery length is 29.5 cm which houses 6 pairs of electrodes. The battery size provides 4.91 cm of a space between each pair of electrodes. Moreover, primary and secondary coil diameter is 4.00 cm which is

¹ Equilibrium/stationary is when battery is neither charging nor discharging.

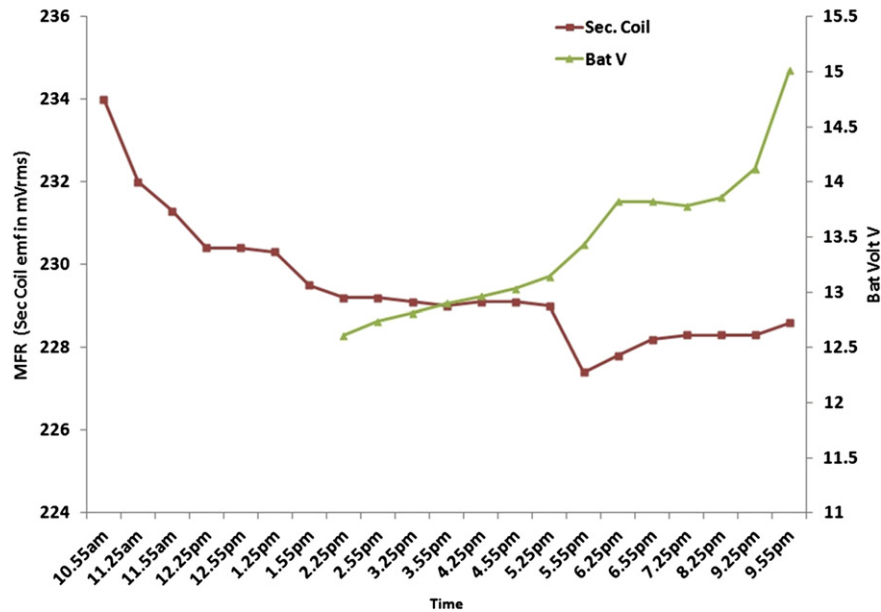


Fig. 5. Magnetic flux linkage reduces with battery charging.

0.91 cm smaller than the space available between electrodes. If electrodes are thinner than half of the 0.91 cm (0.45 cm) then the coils can still have the possibility of facing a free space within the battery. This electrode free space has concentrated H^+ proton electrolyte (during a discharged state of a battery) which causes an improvement in the SCV value. Fig. 10 shows that SCV is higher by 3.6% at the positive electrode than at the negative electrode. Negative electrode Pd repels magnetic flux lines more because Pd has a strong diamagnetic susceptibility ($-23\chi_m/10^{-6} \text{ cm}^3 \text{ mol}^{-1}$) relative to PbO_2 ($-42\chi_m/10^{-6} \text{ cm}^3 \text{ mol}^{-1}$) [4,9].

In the Fig. 11, curve “A” represents the lowest SCV at the top position of the battery which is generally an empty air space used for the electrode connections. The absence of H^+ protons results in a weak magnetic flux linkage between the coils. Curve B shows the maximum SCV, an average 12% higher than at the G position. It records the response of the coil situated at a position near the top

surface of the electrolyte. This surface of the electrolyte, generally, is less concentrated (highest H^+ proton) and thus allows for good magnetic flux linkage. The SCV gradually decreases in the lower layers of the electrolyte, as the electrolyte concentration increases. This can be seen in curves C and G. This gradual decrease in SCV measures the electrolyte concentration gradient vertically in the battery frame and explains the acid stratification in the discharged lead-acid batteries.

4.3. SCV at 3×3 coil positions during battery cycles for current profile and electrode surface structure

This category of observations is related to the experiment with three horizontal and three vertical positions of coils shown in Fig. 12 or in Fig. 3 on the battery frame under the charging or discharging conditions.

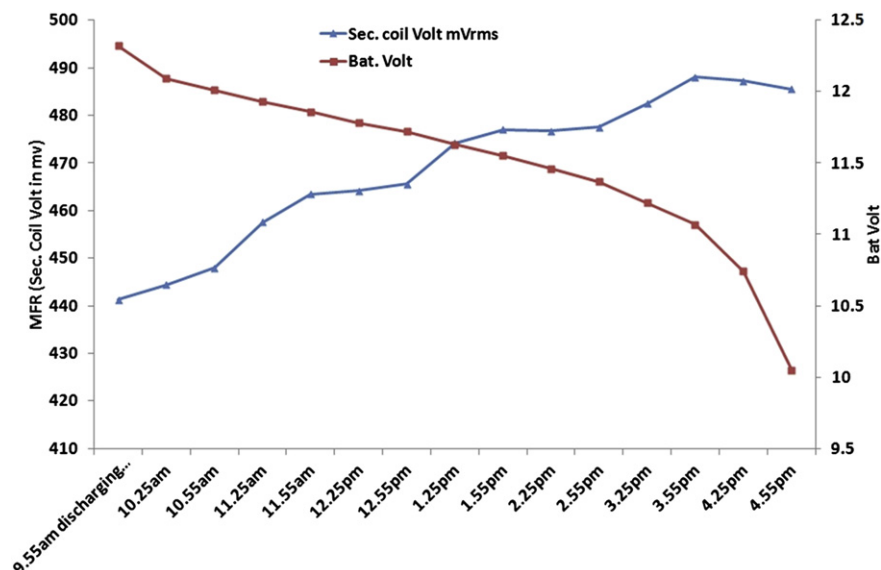


Fig. 6. Magnetic flux linkage increases with battery charging.

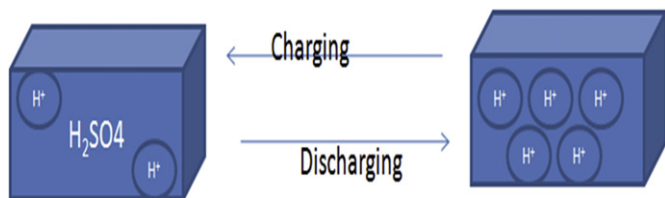


Fig. 7. H^+ proton concentration during charging/discharging of the battery.

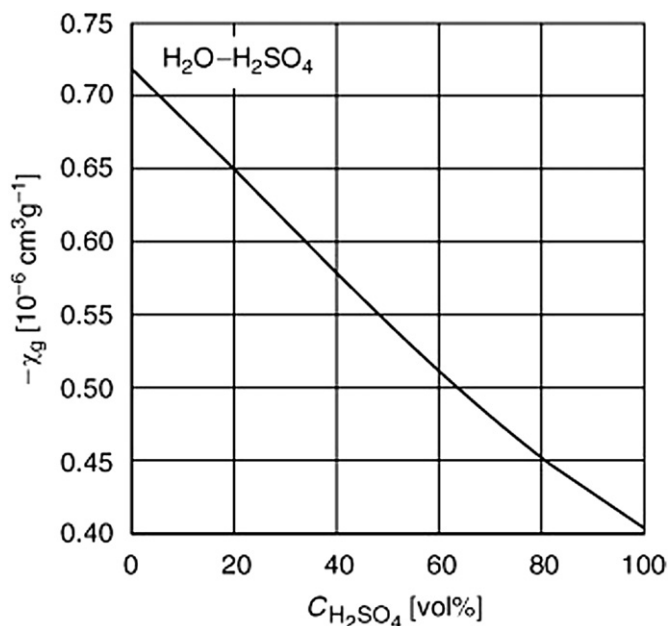


Fig. 8. Mass susceptibility of water mixtures vs. volume percentage of sulfuric acid (H_2SO_4), [9].

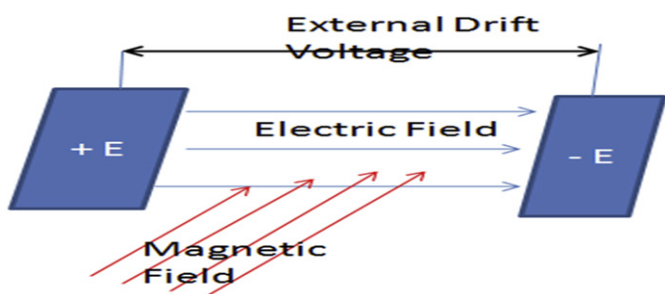


Fig. 9. Effect of BMS connection to the battery terminal.

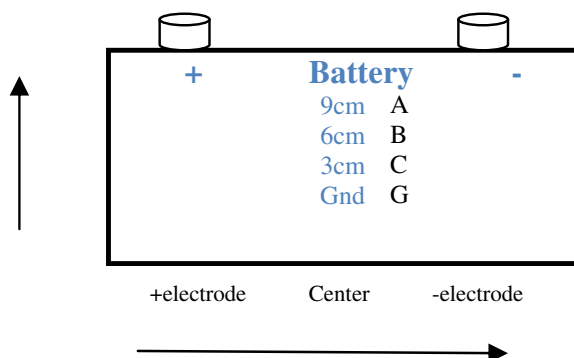


Fig. 10. Coil positions on the battery external frame.

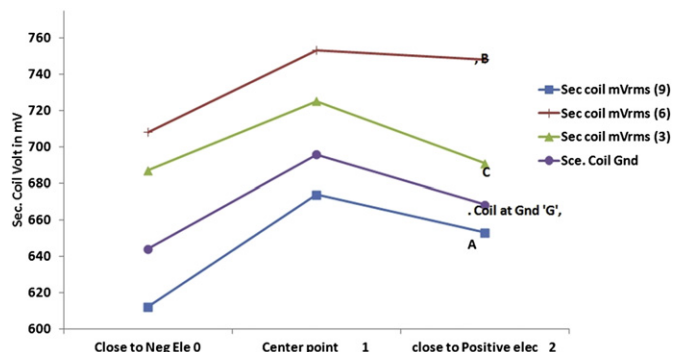


Fig. 11. Varying coil position magnetic flux linkage for battery equilibrium condition.

Battery cycles are observed at 3×3 positions on the battery frame and results are compared for each row and column positions. The measurements were repeated three times at each position and average values were taken for the analysis. The observations are shown here for three column positions: (1) the positive electrode, (2) the center and (3) the negative electrode. Each column position (1, 2 and 3) is further divided in three row positions, the top (A), middle (B) and the bottom (G) as shown in Fig. 12.

4.3.1. Charging process

Figs. 13–15 show SCV during charging of the battery at the positive electrodes, center and the negative electrodes respectively. Each figure organizes the results along a column as shown in Fig. 12.

4.3.1.1. Positive electrode. Fig. 13 describes the SCV at the top, middle and the bottom row positions on the positive electrode of the 3×3 matrix.

Graphs in the figure verify the following observational patterns and analysis previously made: 1) the charging process reduces SCV; 2) the discharged state shows higher SCV compared to the charged state; 3) the BMS charger connection alters the SCV; 4) the SCV gradually decreases vertically down from the top row A to the bottom row G at the positive electrode. Additionally, the SCV at the bottom G1 position does not change significantly. The SCV at bottom row G position does not change significantly during the charging process because concentrated acid (heavy H_2SO_4) accumulates at the bottom layer of the battery that does not allow free H^+ protons to remain at the bottom layer. The lower amount of H^+ protons causes the weakest SCV to register at the bottom layer of the battery.

4.3.1.2. Center column. Fig. 14 describes the SCV at the top, middle and the bottom row positions of the center of battery of the 3×3 matrix. The patterns, though, are quite similar to previous observations in showing higher SCV at the discharged state than at the charged state of the battery and the bottom row G2 does not show significant change in SCV. However, the bottom row G2 shows the opposite pattern upon BMS connection.



Fig. 12. Magnetic coil positions of the 3×3 matrix on the battery frame.

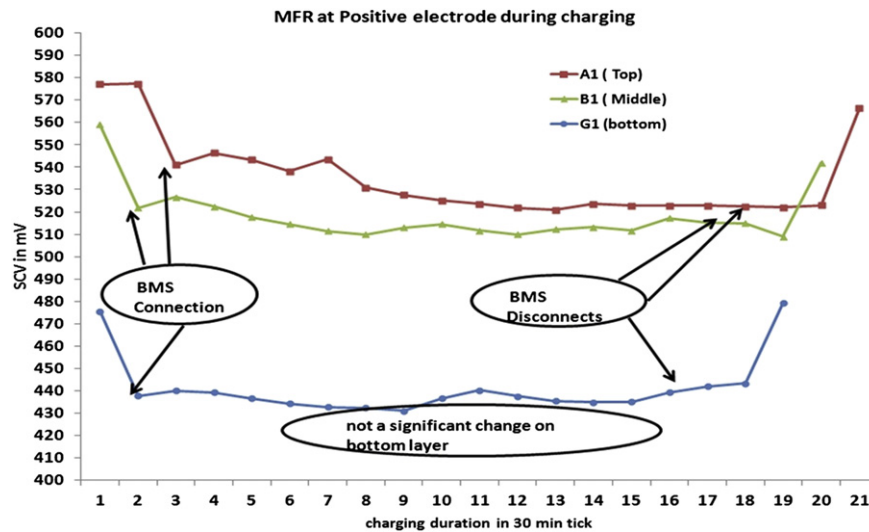


Fig. 13. SCV at positive electrodes during charging.

The SCV is not monotonically decreasing vertically down from A2 to G2. The top A2 and the middle B2 rows show SCV variation approximately of similar range.

In this work, we assumed that at the center column position the coils face the free space between the electrode plates. However, the coils' cross-sectional diameter 4 cm is smaller than the 4.91 cm available space for the electrodes pair in the battery. It is possible that the coils are facing a portion of the positive or the negative electrode during the experiment along with the free space. The efforts are part of an on-going research work to design an experimental setup with coils facing the free space between the electrodes in the battery. Thus, further discussion concerning the center column position will be presented in the future.

4.3.1.3. Negative electrode. Fig. 15 shows the SCV at the top, middle and the bottom row positions of the negative electrode of the 3×3 matrix.

At the negative electrode, the SCV pattern is different than at the other two columns. This electrode does not show a gradual decrease in SCV going vertically down from the top row to the bottom row positions (A3–G3). The middle row B3 shows

maximum SCV at the negative electrode unlike the top row A of the positive electrode. This pattern looks like a vertical Gaussian distribution of SCV or of H^+ proton concentration at the negative electrode as shown in Fig. 16. The maximum SCV at the node B3 indicates the maximum H^+ proton concentration (lowest concentration of electrolyte). The H^+ proton is a primarily consumed particle at the electrodes during the charging process [3]. The H^+ proton Gaussian distribution shows that node B3 consumes less H^+ proton and therefore it is the less active node during the charging process at the negative electrode. The Gaussian distribution possibly explains the reaction centers or current gradients at the negative electrode surface. On the other hand, the gradual decrease in SCV (H^+ proton concentration) at the positive electrode and the center column suggests stratification in the lead-acid battery.

In Figs. 14 and 15, the SCV sharply increases at the bottom row G when connected to the BMS. The sharp increase in the SCV is opposite to the top and middle row responses when connected to the BMS. The BMS connection applies drift voltage on the electrodes which then generates an electric field between the battery terminals. In the design of a battery, none of the electrodes reaches to the bottom row 'G' as shown in Fig. 17. The drift electric field does

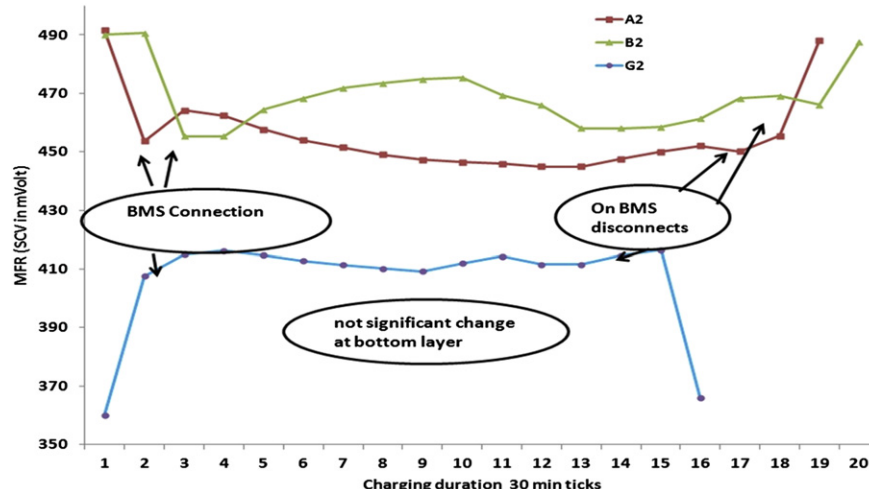


Fig. 14. SCV at center column position during charging.

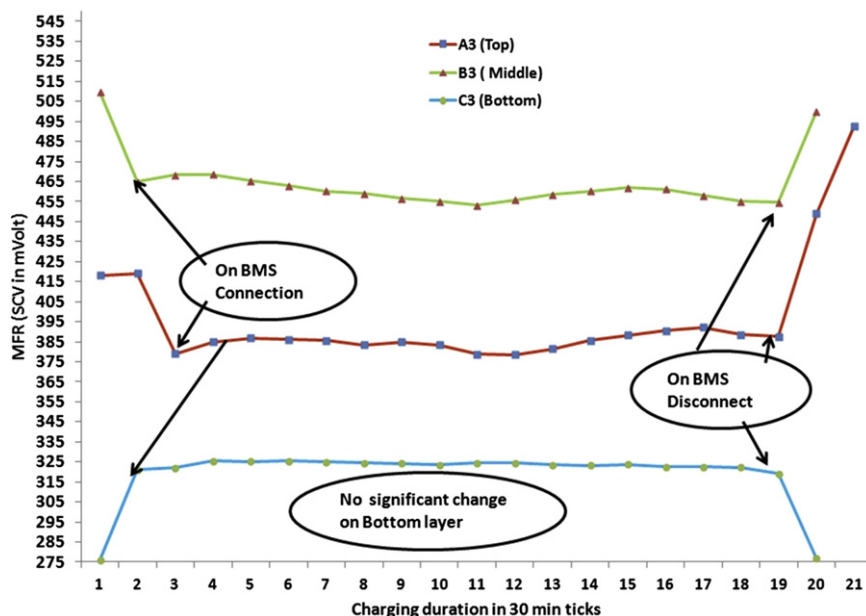


Fig. 15. SCV at negative electrode during charging.

not appear strongly at the bottom layer G and hence it does not screen the magnetic flux linkage. It may also be possible that under the influence of this drift electric field the concentrated acid at the bottom layer breaks into the ions and supports the flux linkage on the BMS connection. This could explain the sharp increase in the SCV on BMS connection at the bottom row.

4.3.2. Discharging process

This section describes the SCV variations during the discharging process of the battery. Figs. 18–20 represent positive electrode, center and negative electrode columns. Each column is further divided into three row positions top, middle and bottom.

4.3.2.1. Positive electrodes. Fig. 18 describes the SCV at positions A1, B1 and G1 for the positive electrode of the 3×3 matrix.

Fig. 18 verifies that the previous observations were accurate, i.e. the SCV increases with the battery discharge and the SCV decreases from top to bottom at the positive electrode. This figure displays similar patterns on the BMS connection to the battery terminal. However, the figure also illustrates that the maximum relative increase in the SCV appears at the B1 position.

4.3.2.2. Center column. Fig. 19 describes the SCV at positions A2, B2, and G2 for the center column of the 3×3 matrix.

In the center column position, Fig. 19 shows similarity with positive electrode patterns (Fig. 18) except that in Fig. 19 the SCV of row A2 and of row B2 are a little closer to each other.

4.3.2.3. Negative electrode. Fig. 20 describes the SCV at three row positions A3, B3, and G3 for the negative electrode of the 3×3 matrix.

At the negative electrode the middle row B3 shows higher SCV and is unlike the patterns at the positive electrode and center column of the battery. However, the higher SCV at row B3 is similar to Fig. 15 at the negative electrode during charging. Like other patterns, Fig. 19 also displays SCV increases during the discharge process, negligible change at the bottom row G3 and similar patterns on BMS connection.

During the discharging process of the battery, the SCV is mostly analogous to the previous observations. The observations above verify that: (1) SCV increases with the discharge of the battery, (2) the discharged state always shows higher SCV compared to the charged state of the battery, (3) the concentration gradient of H^+ protons at the positive electrode and at the center column follows similar pattern and shows stratification of the electrolyte. On the other hand, H^+ proton concentration at the negative electrode follows exactly the same pattern as in the charging process shown in Fig. 16. It is possible that the concentration patterns reflect the

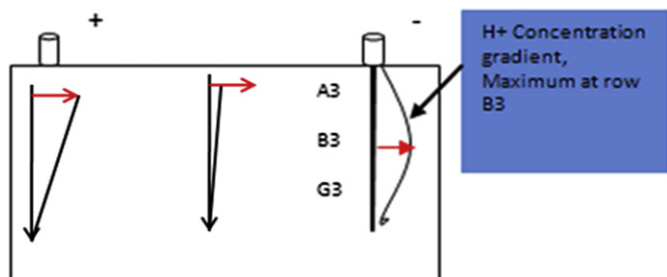


Fig. 16. Magnetic flux linkage or H^+ proton concentration gradient at negative electrode.

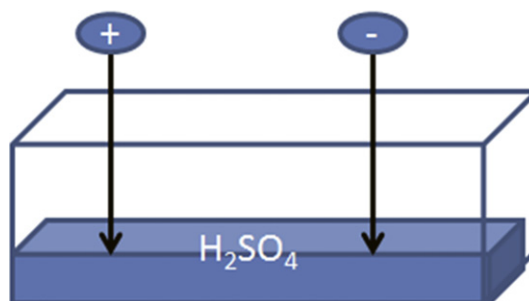


Fig. 17. Electrodes position inside the battery.

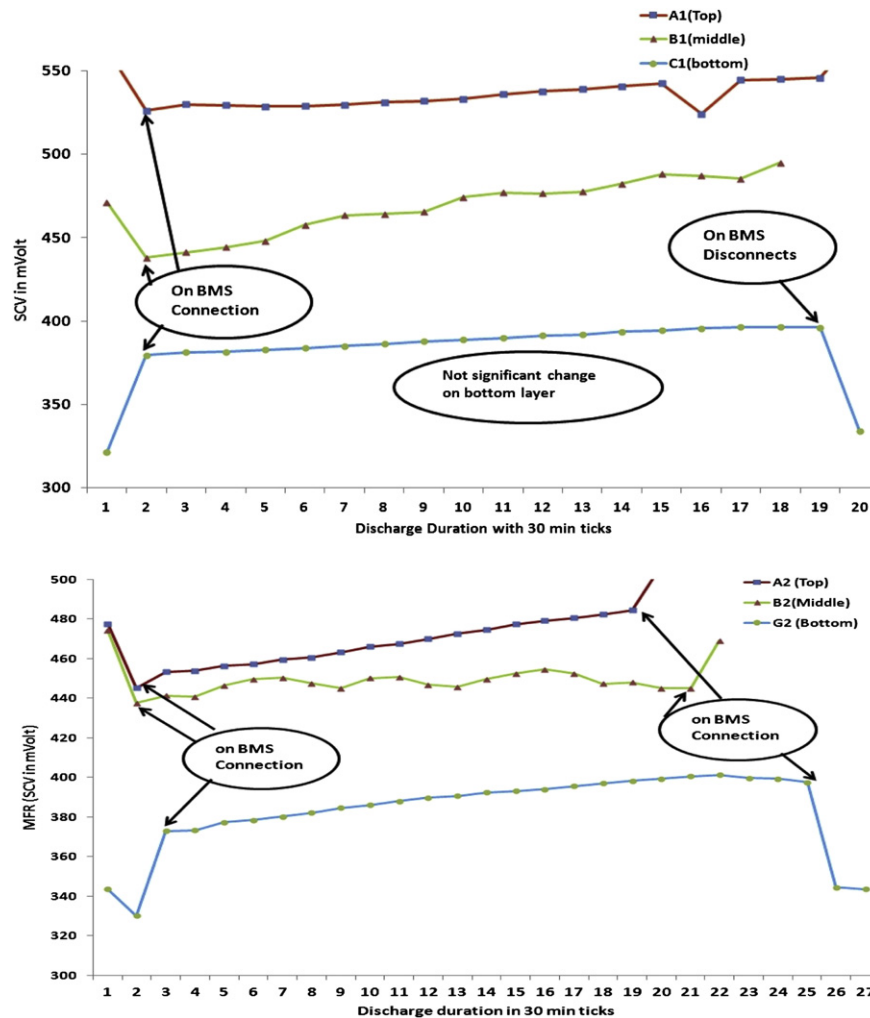


Fig. 18. SCV at positive electrodes during discharge.

structure of the negative electrode or the reaction center at the negative electrode as explained in Section 4.3.1.

In addition, during the discharge process, the relative SCV demonstrates a unique pattern. The relative SCV represents the

change in SCV from the start of the discharge process to the end of the process. The maximum relative SCV occurs at the different row positions in each column during the discharge process. At the positive electrode the maximum relative SCV appears at the middle

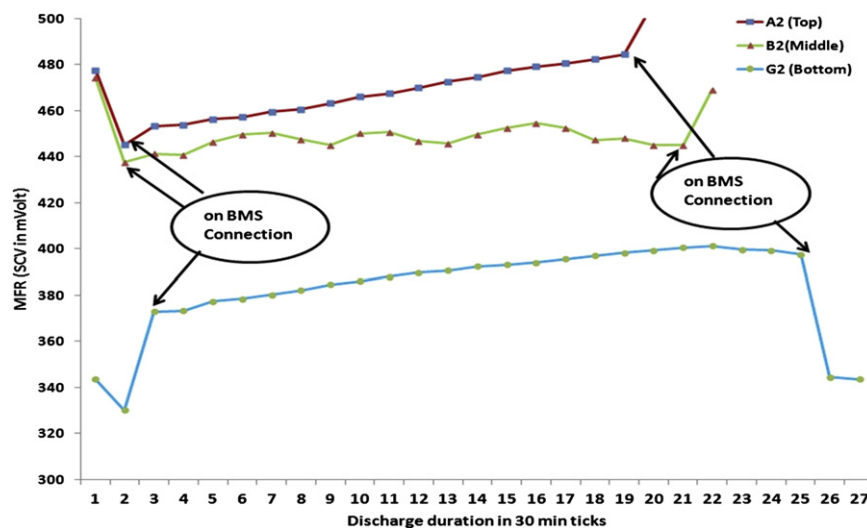


Fig. 19. SCV at center column position during discharge.

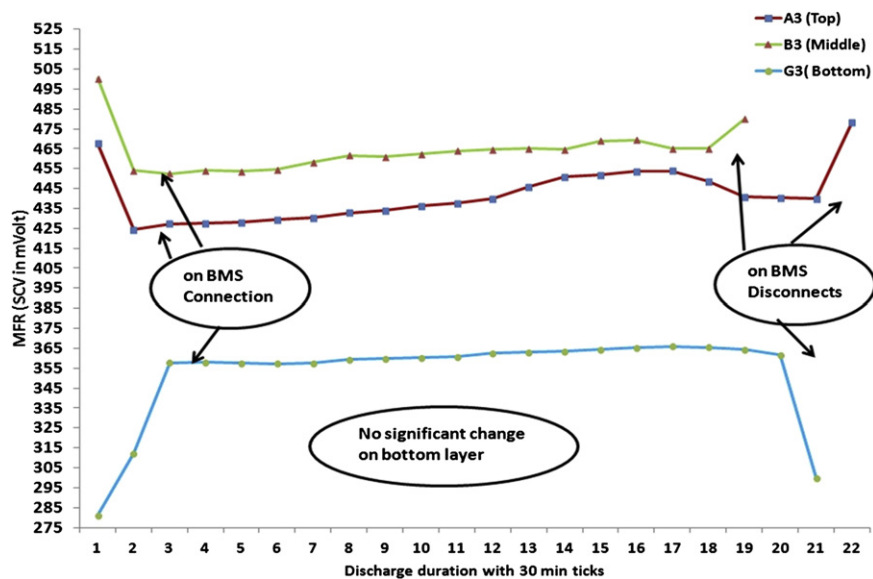


Fig. 20. SCV at negative electrode during discharge.

B1 position. However, at the center column and negative electrode, the maximum relative SCV occurs at the top positions A2 and A3. The discharge process primarily consumes OH^- ions which are heavy and slow to diffuse [3]. This makes discharge a non-homogeneous process. At the nodes, the relative SCV change clearly relates to the high concentration of H^+ protons and lack of OH^- ions, which suggests large consumption of OH^- ions at these nodes during discharge process. Hence, the middle (B1) position at the positive electrode and top (A2, A3) at the center and negative electrode are active reaction nodes that consume larger OH^- ions compared to other nodes during discharge.

Also, a possible high reaction rate (fast reaction) creates more ions in the electrolyte and on the surface of the electrode (nodes). Over the discharge time, these ions increase the SCV at certain nodes which are then considered to be active nodes on the electrode. The presence of active nodes on the electrodes offers the potential to study electrode structure more closely.

4.4. H^+ proton concentration gradient charts

The observations with the 3×3 matrix positions of magnetic coils on the battery external frame measure the H^+ proton concentration. The concentration profile is shown in Fig. 21(a, b) in a 2D frame of the battery during charging/discharging process. In the figure, the arrows are pointing to the relative change from higher to low H^+ proton concentration which we consider a dominating factor for MFR change between row and column positions (nodes). Fig. 21(a and b) depicts the beginning and the end state of H^+ proton during the dynamic process of the charging/discharging at the 3×3 positions of coils. The black arrow represents the starting MFR (SCV) and the red dashed arrow represents the end value of MFR (SCV).

The source nodes suggest higher accumulation of the H^+ proton and sink nodes show the opposite behavior. The figure suggests that positive electrodes always have higher H^+ . It seems the higher MFR at the positive electrode is due to H^+ protons because if electrode susceptibility plays a role then the MFR should be high during the beginning of discharging (due to lead oxide) but not at the beginning of charging when the electrode is lead sulfate. The figures give a clue about H^+ accumulation and diffusion direction during the process. More careful experimentation can provide

reaction centers and current profile in the battery during the charging and discharging processes.

Fig. 21(a, b) demonstrates the higher concentration of H^+ protons at the positive electrode during the charging and/

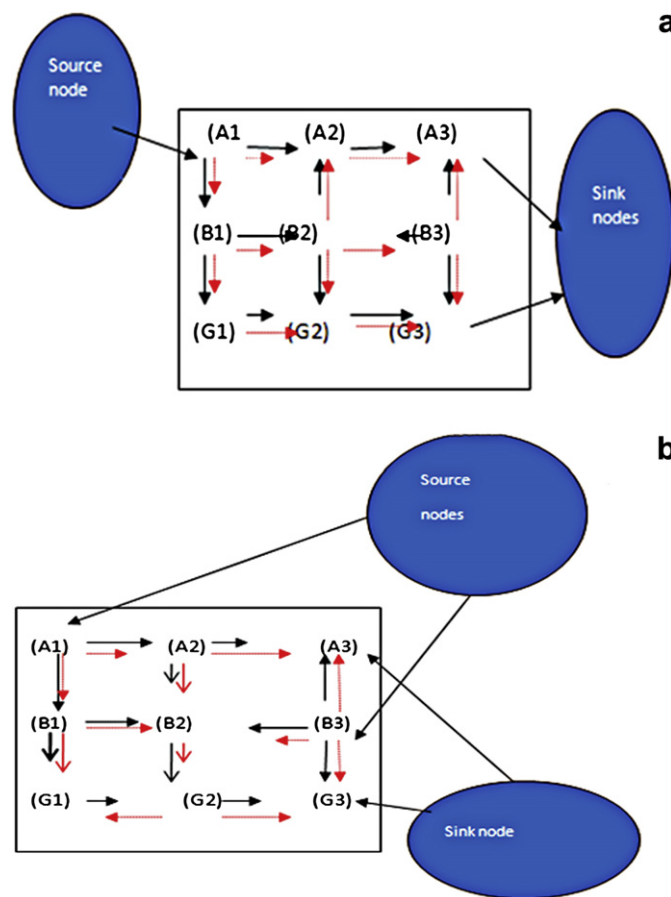


Fig. 21. H^+ proton concentration gradient of (a) charging process and for (b) discharging process of the battery source node has maximum H^+ proton concentration and sink node has minimum H^+ proton concentration.

discharging process. The H^+ proton is the primary ion consumed by electrodes during charging and the OH^- ion is consumed during discharging. This explains why the positive electrode is an active electrode during discharging but not during the charging process.

Knowledge of the concentration gradient profile can, potentially, explain the reaction rate profile on the electrodes, the electrode structure and electrolyte stratification inside the battery during the charging and discharging processes. This needs to be further explored in order to draw a more definitive conclusion.

5. Conclusions

This paper demonstrates the potential of the MFR probing method as a battery health diagnostic tool. The MFR is a non-invasive way to measure SOH of an SLA battery by indicating stratification, electrode structure and current profile within the battery. In the study, we have used SCV as a performance index for battery behavior in an applied magnetic field. The magnetic flux linkage between primary and secondary coils increases when the battery slides between the coils. The increase in the magnetic flux linkage is seen in terms of SCV increases of 120–130%. The fully discharged battery shows at least 10–12% higher linkage of magnetic flux in comparison to the fully charged battery. The connection of the BMS charger generates polarization between electrodes by applying drift voltage and this screens perpendicular magnetic field. The BMS connection reduces the SCV by 25–30%. The observation leads to establishing a relation between polarization resistance and SCV (magnetic flux linking). The discharged

battery, when in the stationary condition, decreases 12% in SCV from the top surface to the bottom of electrolyte in the battery which suggests stratification in the electrolyte. The charging and discharging cycle patterns, in SCV measurement, provide a clear indication about active and passive nodes at the electrodes. This study shows a possibility to analyze the electrode surface structure using MFR variation and also the electrodes' non-homogeneous participation in the charging and discharging process. Recording the electrodes health indication and measuring the electrolyte stratification during run-time can serve as an improvement of the battery SOH.

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